

Design of Large Scale Virtual Equipment for Interactive HIL Control System Labs

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Abstract—This paper presents a method to design high-quality 3D equipment for virtual laboratories. A virtual control laboratory is designed on large-scale educational purpose with merits of saving expenses for universities and can provide more opportunities for students. The proposed laboratory with more than thirty virtual instruments aims at offering students convenient experiment as well as an extensible framework for experiments in a collaborative way. hardware-in-the-loop (HIL) simulations with realistic 3D animations can be an efficient and safe way for verification of control algorithms. Advanced 3D technologies are adopted to achieve convincing performance. In addition, accurate mechanical movements are designed for virtual devices using real-time data from hardware-based simulations. Many virtual devices were created using this method and tested through experiments to show the efficacy. This method is also suitable for other virtual applications. The system has been applied to a creative automatic control experiment course in the Harbin Institute of Technology. The assessment and student surveys show that the system is effective in student's learning.

Index Terms—control systems, 3D equipment design, virtual laboratory, real-time animation, control education, hardware-based simulation

1 INTRODUCTION

IN the learning of control systems, students not only have to acquire theoretical knowledge, but also the ability to apply theory into practice. Practical skills are mainly acquired in experiments. But, as we know, conventional laboratories have the following limitations: 1) equipment for control engineering experiments is often expensive; 2) equipment usually needs to be shared by students in groups; 3) both lab opening hours and space are limited; 4) experimental sessions are always detached from theoretical courses. New laboratories based on varied frameworks have been established due to the outstanding advantages of web and computer technologies in the past few decades. Many papers have been published in recent years on remote laboratories [1-7] and virtual laboratories [8-19].

In web-based laboratories with physical devices, users can conduct real experiments remotely through user interfaces and web cameras. Many remote laboratories have been developed in recent years. Fraile-Ardanuy et al. described development of a remote lab for teaching methods of starting an induction motor [1]. Vargas et al. presented a remote lab, in which students can carry out experiments and observe results through a digital video server with cameras. An approach based on a Client/Server (C/S) framework was presented using Easy Java Simulations (EJS) for the client side, and LabVIEW for the server side [2]. The state of the plant (real device) could be observed

by static pictures with augmented reality animation in the recent work of Chacón et al. [3]. Based on this architecture, Sáenz et al. used low-cost hardware to control remote devices instead of using a personal computer to save on expenses and space [4]. In addition, plugins are developed to deploy the remote lab built with EJS into Moodle for a collaborative experimental session [5]. In a Browser/Server (B/S) architecture, users could remotely carry out experiments using a simple web browser installed on a PC or a mobile phone [6]. Mobile technologies along with Hypertext Preprocessor (PHP) and JavaScript enabled users to carry out experiments using portable devices outside the classroom. Compared with the C/S architecture where a client setup is required, the B/S architecture is more easily accepted by users for its convenience. A remote laboratory makes it possible to share resources between universities, and smart web cameras are usually introduced into the system in order to collect visual information about remote devices. To enjoy the process of a control experiment better, students are always eager to watch the device in varied views and observe it in detail. Although more cameras can be installed around the device and views can be zoomed in and out with advanced cameras, it is still not easy to provide sufficient internet speed for high resolution videos especially in network congestion circumstances. Moreover, because the transmission of video streams is very bandwidth-consuming, the internet service bills charged according to the server data flow could be very costly. L. M. Jimenez et al. presented a remote control laboratory using Matlab and Simulink [7]. They transmitted video streams in order to observe experimental results, which was rather bandwidth-consuming. Therefore, it is not suitable for

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large-scale applications compared with 3D animations.

Virtual laboratories (compared with remote laboratory) are web-based laboratories using simulations. In literatures, several approaches have been proposed using virtual technology to solve different problems on education. In [8], a PC based virtual instrument with a data acquisition (DAQ) board was used in a magnetic circuit experiment to give lively presentation of a magnetic field. In [9], a virtual instrument system in reality is developed for electronic circuit practice. In [10], a virtual laboratory was developed for students to design, configure, and debug a network scenario. The system would be more powerful if it allowed many users to log in at the same time, as mentioned in their future work. In [11], a virtual lab of multimedia systems on DSP concepts was presented to enhance the comprehension of the material taught, which allows students to learn complicated theory through interactive GUIs. A LabVIEW-based virtual instrument was designed to show real-time information about a magnetic field intuitively [12]. Two approaches were presented in [13] that can help to develop virtual control experiment labs quickly and simply using software tools: Modelica library and Rand Model Designer. A virtual laboratory platform based on cloud servers was presented in [14] for learning and practicing on virtual networks. A study finds that using virtual labs for experiments can have similar effects on students' learning to using traditional labs [15]. Although a student-centered self-learning methodology is strongly recommended, it is still necessary to turn to teachers for help when facing obstacles. In [16], a 3D Modelling Educational Environment (3DMEE) is presented as a web-based virtual teaching system with advanced user interfaces, which provides students many resources in a virtual classroom as well as real-time communication with a teacher. A 3D virtual laboratory was presented in [17] for wiring experiments on microprocessor units and breadboards. The system is helpful to students in microcomputer interface education. An online exhibition application with Flash 3D and Flex SDK based on PureMVC framework was presented in [18], which shows Flash technology is a power tool in 3D animation.

Taking experiments "online" is not adequate for virtual laboratories at present, and students are more interested in

virtual labs which are visually appealing and easy to use [19]. The above work based on various techniques is excellent, and verified to be helpful in the teaching field. However, many virtual laboratories may still be improved if they can provide some of the following contents: 1) abundant virtual resources; 2) lively virtual devices with appealing animation effects; 3) accurate dynamic movement of 3D models compared with physical devices; 4) framework suitable for large-scale applications; 5) compared with personal computers, embedded hardware systems are usually less expensive and can be used as simulators or controllers to save cost.

If the simulation of a real controller can be called as a virtual controller, and the simulation of a real device can be called as a virtual device, there are three combinations in a control system: 1) a system consisting of a virtual controller and a virtual device is a pure simulation system; 2) a system with a virtual controller and a real plant is a rapid control prototype (RCP) system, which is a semi-physical system; 3) a system with a real controller and a virtual device is a HIL simulation system, which is another kind of semi-physical simulation systems whose plants are modelled and loaded into a real time simulator. HIL simulation is an effective tool for the verification of control algorithms [20]. HIL systems can improve test efficiency and save cost, and always work with a 3D visualization for the presentation of a real device, e.g., a DSP and FPGA based HIL UAV testing platform [21], an automatic train control system (ATC) [22], an FPGA-based model of inverted pendulums [23], and a container crane device [24]. Furthermore, HIL experiments have been shown to be very useful, especially when integrating components of several partners in a complex research project [25]. In [26], a HIL simulator was proposed to simulate dynamic systems in non-real-time for engineering education. But, the model of the simulated plant along with its auxiliary inputs must be predefined by the administrator. Compared with this work, our simulators can run real-time simulations, which are much closer to the real world. Also, users can change the inputs and the parameters of the model during the experiment. HIL simulations are safer than traditional ones, e.g. a physical rotary inverted pendulum needs to be fixed into the cement

TABLE 1
COMPARISON OF VIRTUAL 3D LEARNING SYSTEMS

Systems	Number of virtual devices or experiments provided	Simulations	Support realistic 3D performance	Collaborative experiment	Complex 3D motion
UNILabs	3 virtual devices	Simulations based on differential equations supported by EJS	No	No	No
UNEDLabs	15 collaborative experiments	Simulations based on differential equations supported by EJS	No	Yes	No
Microcomputer interface Virtual Lab	1 experiment	No	Yes	No	No
VESLL	Several	No	No	No	No
Virtual crane system	1 experiment.	Real-time simulation based on simulator	Yes	No	Yes
3D-NCSLab	30 virtual equipment	Real-time simulations based on Matlab server and ARM-based simulator.	Yes	Yes	Yes

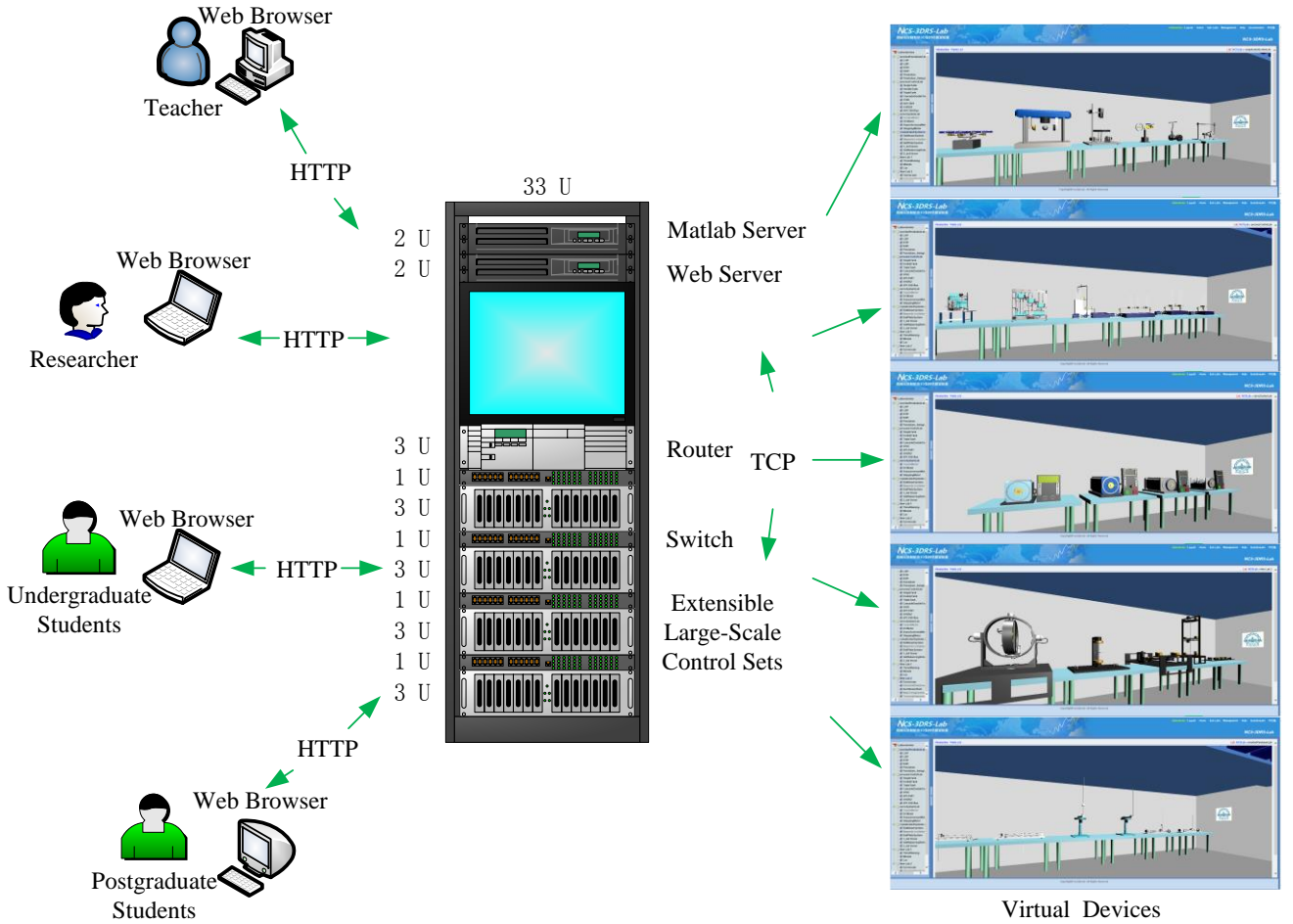


Fig. 1. Architecture of 3D-NCSTLab. The system consists of Web Server, Matlab Server, extensible large-scale control sets, and virtual devices for automatic control experiments. The system can meet the requirements of users at different levels, and provide large-scale experiments by the extensible control sets. In addition, more virtual devices can be created and implemented into the system based on this architecture.

of the ground to make it stable, otherwise it may hurt people. Another merit of HIL applications is that we can conduct simulations on issues with big-sized plants or in a wide terrain environment, such as vehicles, satellites, and missiles. The practical experiment environment is difficult and expensive to set up. So, HIL simulation with interactive 3D animation is a sound and feasible way to handle the problem.

There are other kinds of virtual labs using collected experimental data of physical devices. However, as the triggered outputs including either videos or diagrams need to be prepared ahead of use, the experimental result is predetermined and lacks in flexibility. There is a paradigm shift from remote labs with physical equipment to virtual labs with real-time HIL simulation for large scale application purpose [27]. A remote laboratory with 3D animations based on a Flash Proscenium engine was presented in [28], users were able to carry out experiments remotely through cameras as well as 3D animations. In this paper, 3D-NCSTLab with powerful virtual equipment and integrated control hardware is presented, based on NCSTLab framework [28], [29], [30]. Compared with [28], this paper aims at low-cost large scale applications with virtual devices instead of

physical ones. And a method is proposed to design realistic virtual devices with complex mechanical characteristics. More than thirty virtual devices have been designed using this method; and with the newly designed large scale integrated hardware, the system can offer more resources and experiment opportunities for student. Also, collaborative and innovative experiments are presented to illustrate the flexibility of this virtual experiment framework. In addition, this method could inspire users to design their own virtual devices in a creative style. A more specific comparison of the methods is presented in Table 1.

To address the aforementioned problems, a methodology of using large-scale virtual equipment in place of physical devices on education is proposed in this paper. Three Dimensional Networked Control Laboratory (3D-NCSTLab) was developed for control engineering experiments, see Fig.1. Students can carry out experiments on web-based virtual labs from anywhere, at any time, as long as they can get access to the internet.

In virtual experiments, students can on-line design algorithms using provided mathematical models. Both transfer function and state space equations are provided on the system. A cascade PID algorithm is designed by a

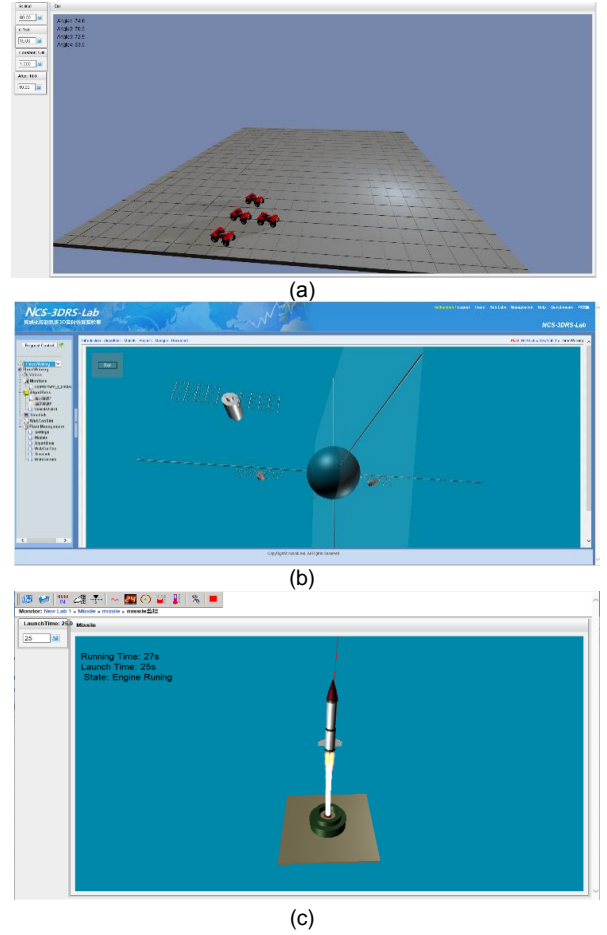
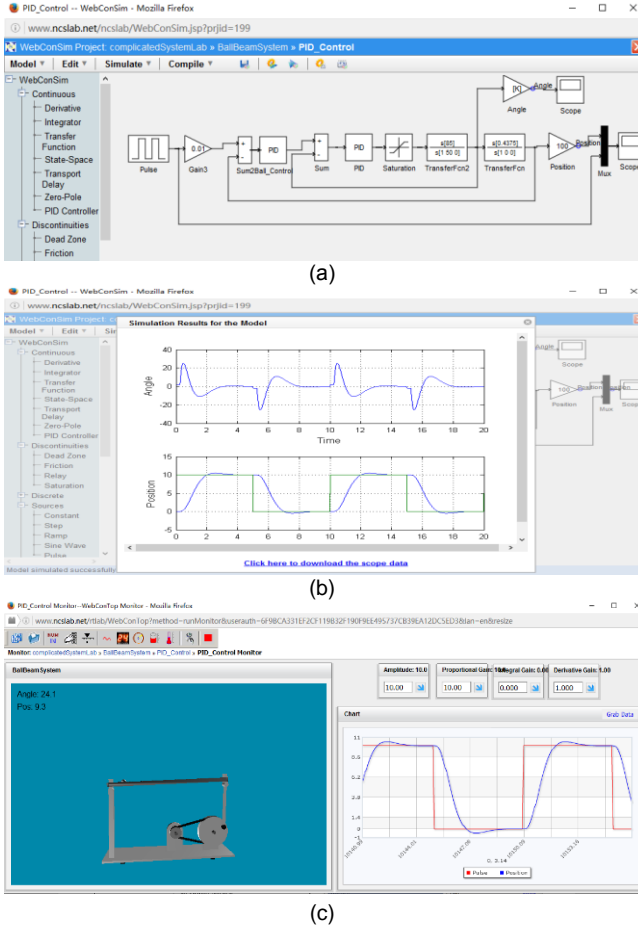


Fig. 2. (a) Web-based algorithm design interface. (b) Simulation result of a cascade PID algorithm. (c) 3D real-time experiment with an interactive virtual device and a dynamic chart.

Fig. 3. Three creative virtual experiments designed by postgraduate students. (a) Vehicle formation control. (b) Satellites formation control. (c) Missile trajectory design.

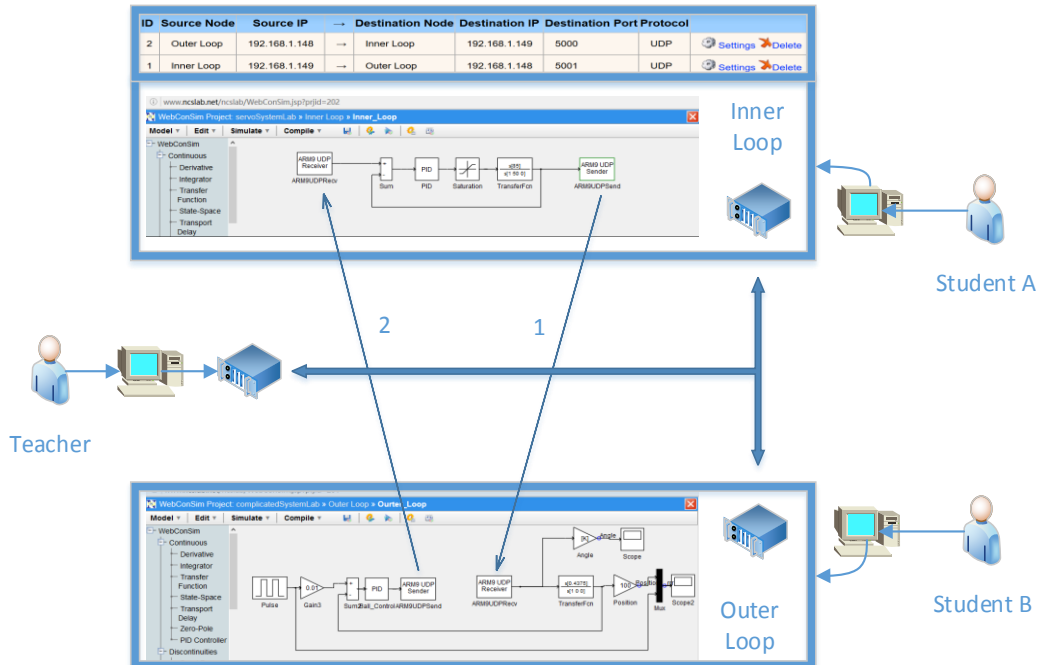


Fig. 4. Collaborative control framework of ball and beam system carried by two students. Students A controls the servo position in the inner loop and student B controls the ball position in the outer loop. The data is transmitted between control units via UDP. The teacher can check students' work by receiving real-time data from control unit.



Fig. 5. Extensible large-scale control sets based on ARM microprocessor and embedded system.

student and applied to a plant on the web-based interface as shown in Fig. 2(a). Simulation results can be seen in the scope as shown in Fig. 2(b). A dynamic chart is used to display the real-time response curves. Both the controller parameters and reference signals can be modified via input

modules. The real-time experiment interface is shown in Fig. 2(c).

On the one hand, 3D-NCLab can provide high-efficient experiments with rich contents; on the other hand, it inspires students to create new experiments and test new ideas. Students may gradually lose their positive motivation in an isolated learning environment. The system can arouse their enthusiasm by providing collaborative experiments. 3D-NCSLab enables real-time data exchange between IP based control units via user datagram protocol (UDP), thus a real-time control experiment can be divided into a few parts. To run the whole control system, collaborative students need to finish their own work, and link their data using communication blocks. In Fig. 4, student A uses a PID controller to control a servo motor as the inner-loop, he receives control signals from student B and sends servo position signals via port 5001 to student B; student B uses another PID controller to control the ball position as the outer-loop, he receives signals from student A and sends ball position signals via port 5000 to student A. This framework is flexible and also enables a teacher to receive real-time data from student A and student B.

For intermediate level and advanced users like postgraduate students and researchers, 3D-NCSLab encourages users to create their own experiments and integrate them into the system. First of all, they need to design a virtual equipment using methods presented in this paper.

Secondly, the virtual device and virtual laboratory can be created on webpages, which is a functionality of the system, and then monitor interfaces and buttons should be set up. Next, the virtual device can be debugged using test signals and finally new virtual device can be used in experiment. Some examples carried out on the open platform by postgraduate students such as vehicle formation control, satellite formation control, and missile trajectory design are shown in Fig. 3.

This paper is organized in the following way: in Section II the architecture of the system and its functionalities are described. The method of designing 3D virtual devices is presented in Section III. Section IV presents the assessment. Finally, conclusions and future work are given in Section V.

2 SYSTEM DESCRIPTION

2.1 3D-NCSLab Overview

The 3D-NCSLab system consists of two servers and large scale control sets, and provides rich functionalities, such as user accounts and authorization management, device and experiment management, algorithm design, simulation, compiling and downloading, 3D real-time experiments. The web server is primarily based on Tomcat 6.0, MySQL database, Java, JSP/Servlet technology. It provides main functionalities of the system, except that online simulation and compilation are realized on a Matlab server. The hardware of the control units is mainly based on high performance ARM microprocessors and Linux 2.6 operation system. The control units are connected to the system via a RJ45 network port to exchange data. As a controller,

a control unit outputs control signals to physical equipment; and as a sensor, a control unit collects data from the equipment. The control units are redesigned to be more concise without an AD and I/O board for virtual experiments. By virtue of reduced size, up to 20 control units can be embedded into one single large control set, as shown in Fig. 5.

Running several control sets together, the server is able to provide experiments for multiple users simultaneously. The server guarantees allocating one control unit to each user; if there are not enough controllers available, users are required to wait in the queue. Users can easily get access to an experiment via the Internet. Also, the system offers different experiment modes according to user's level. The researchers are able to work on physical devices connected to DAQ of the system to control it remotely with specifications like disturbances from a real environment. Teachers can online supervise students' real-time experiments in 3D monitor interfaces. Postgraduates are encouraged to create their own virtual devices for innovative experiments. Undergraduates can carry out virtual experiments based on hardware-in-the-loop simulation as an effective substitute for physical experiments.

2.2 Issues and Challenges

A plant is one of the most important components in a control loop. However, it is economically impractical for large-scale applications. Given that, twenty undergraduate students are going to conduct experiments on their own devices and each of them has four different experiments during the semester, to meet this demand, eighty physical devices in total need to be allocated to students. It will cost a large amount of money to purchase the devices, let alone the place for equipment and the additional manpower to maintain the facilities.

To address the above problem, real devices are replaced with virtual devices. A virtual device for automatic control experiment designed in this paper consists of three parts: 1) a realistic 3D model; 2) similar mechanical characteristics compared with real device; 3) a mathematical model described with state-space functions, transfer function, or S-function. Real-time data from simulation on the mathematical model is used to drive the virtual device. Developing these three parts mentioned above is not an easy task, and challenges include how to design a virtual device that moves in a similar manner to a real device, how to describe a real device in a mathematical model as accurately as possible, and how to make the 3D model realistic and appealing to users.

2.3 System Functionalities

2.3.1 Algorithms Design and Simulation

Algorithms are central issues in control system experiments. In 3D-NCSTLab, practical devices are represented by mathematical models. Detailed instructions for experiments as well as algorithm demos are both provided on the system. Users can run a simulation demo as an exercise.

Also, since very detailed values of structural and electro-mechanical parameters are provided, users can construct the mathematical model of the system to understand the system better. For advanced users, complex models with uncertainties or mechanical nonlinearities can be described by S-Functions.

Users are able to design their own algorithms in a web-based graphic user interface (GUI) without installations of plug-ins. Common-used simulation blocks as well as networked communication blocks are provided, which can be dragged into a diagram. By simply connecting the blocks with signal lines, and by setting simulation parameters like start time, stop time, fixed step size and solver, the simulation is ready to run. When a remote simulation is finished, results can be viewed through scope blocks in the diagram. The control performance can be tuned by adjusting parameters until requirements are met. Important data can be saved for future use.

2.3.2 3D Real-time Experiment

A real-time simulation is carried out in fixed discrete time (also fix step and sample time) as "real world" time runs forward in equal duration. The time used to solve the internal state equations and functions must be limited in a sample time. A real-time simulation needs to figure out the internal variables and outputs within a fixed step as its physical counterpart does. The real-time operating system (RTOS) is adopted to serve real-time applications as its processing time is measured in tenths of seconds or shorter increments of time. In this article, the design chose Linux 2.6.23 kernel patched with Real Time Application Interface (RTAI) 3.8 to make the onboard operating system real-time [31]. An FPGA-based real-time simulation system was presented in [32], which had a microsecond level simulation step size. In comparison, our Arm-based embedded system has a millisecond level simulation step size. It is proved to be adequate for control engineering experiment.

Configuring models to run in real time enables users to use hardware-in-the-loop simulation to test controllers [33]. Users can make design changes earlier in the development process, reducing costs and shortening the design cycle. But, as 3D-NCSTLab system is designed on educational purpose to carry out control experiments for undergraduate students, we have to focus on issues like control algorithm design, real-time control performance and the learning process. Hardware limitations (as number of the bits, real time problem, ...) are a little hard to understand for undergraduate students. Instead, we hope to carry out this promising idea in our future research.

First, in the compiling process, the Simulink model file is compiled into C codes by real-time workshop (RTW). Then, executable codes that can run directly in Linux systems are generated from C codes by CygWin GCC. The Supervisory Control and Data Acquisition (SCADA) server can offer real-time signals to experiment engine for remote monitoring. The experiment engine stores data in real-time buffers and provides real-time data for 3D devices. 3D-NCSTLab offers rich resources on the monitor interface including 3D Flash controls, dynamic charts, input modules,

signal display modules, etc. 3D animation modules are deployed in the monitor interface by AJAX scripts. Users can easily customize the interfaces by dragging modules and selecting corresponding signals from the data list. Fig. 6 shows the mechanism of the system and detailed information about data flow during the experiment.

3D models are loaded in the scene from database and displayed in a virtual environment according to the XML configuration. As soon as a real-time experiment starts, the experiment engine will continuously send request to the control unit and collect data to drive the virtual device. A 3D model runs vividly with real-time data, at the same time users can tune parameters on the monitor interfaces.

Any user's operation to the parameters on the monitor interface will automatically update the values of the corresponding model variables. So, users are able to control and interact with a virtual device in a friendly way. It allows users to observe the details of a virtual device in flexible views by simply dragging the mouse. It is also an efficient way to conduct a control experiment.

3 DESIGN OF VIRTUAL EQUIPMENT

3.1 Method to design 3D virtual equipment

The method to design a high-quality virtual device contains a few steps. First, we need to construct a 3D model. Then, we add rendering and lighting to the scene. Next, we

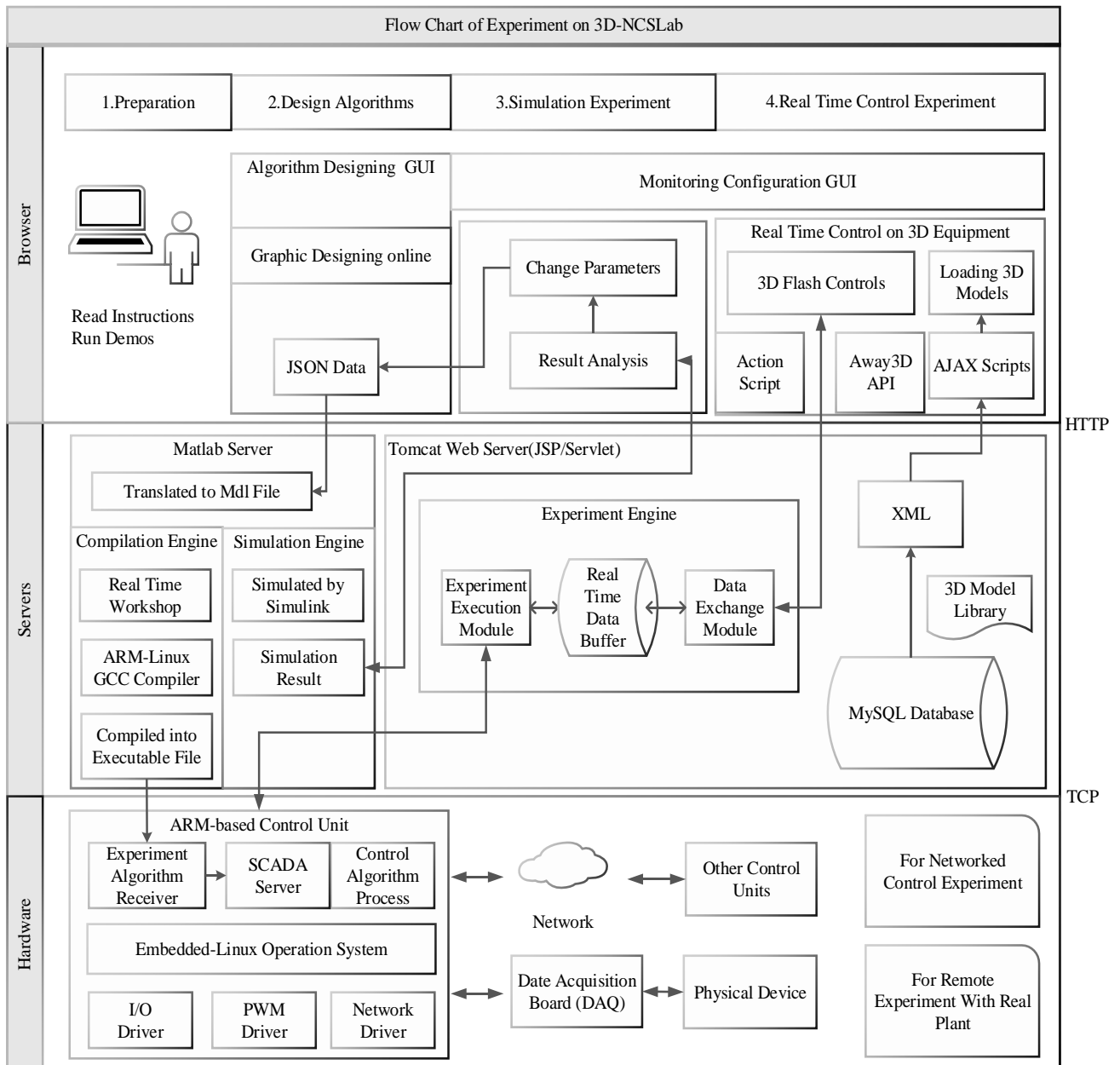


Fig. 6. The flow diagram of system key functions. The system is described in three parts: browser, server, and hardware. The connections among the modules are given in the process of four experiment phases: preparation, algorithm design, simulation experiment, and real-time control experiment.

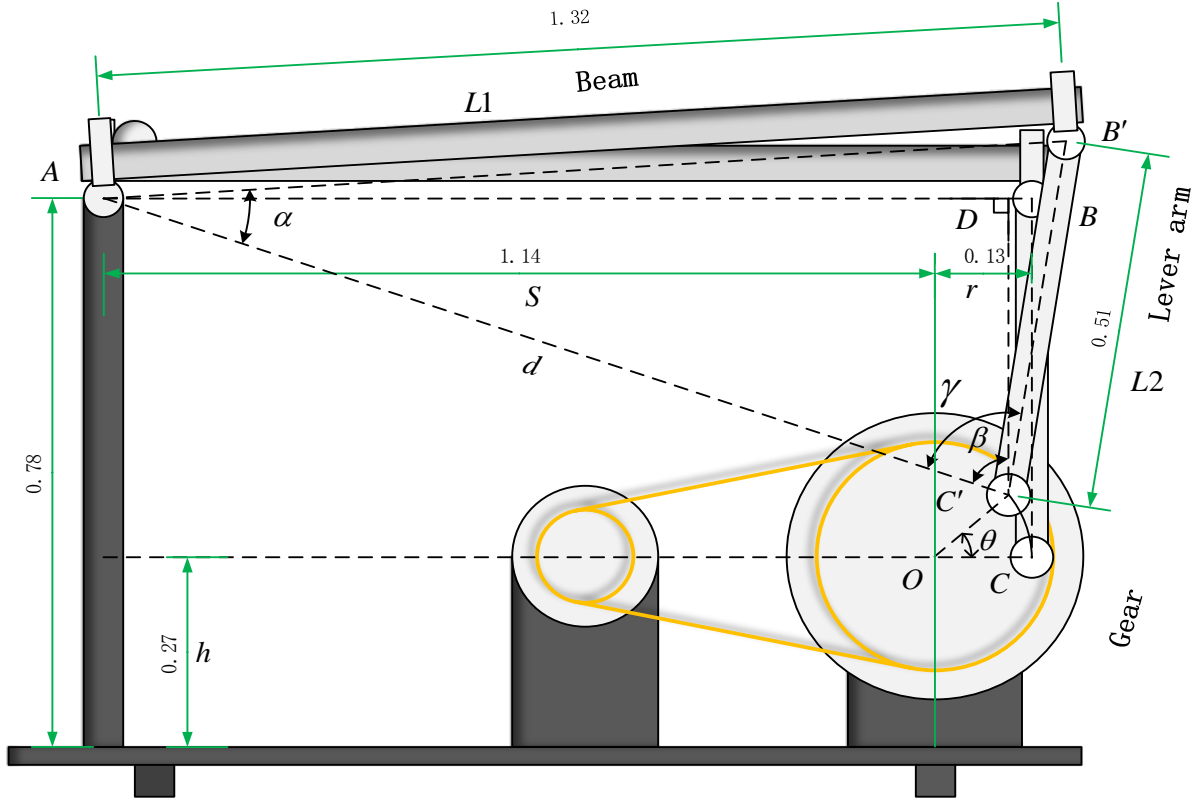


Fig. 7. The schematic diagram of a ball and beam system. The structure is carefully analyzed to realize an accurate representation of the mechanical movements.

make mechanical animations for the model. At last, we add interactive interfaces for users to control the views. The animation should act in the same way as a physical device. So, the accurate presentation of mechanical movements plays a key role in making virtual devices.

3.1.1 Modelling

A 3D model of the physical device needs to be created first using 3D modelling tools. In this work, both virtual equipment and virtual buildings of 3D-NCSLab are modelled in the 3ds Max. The 3ds Max software offers varied tool sets for developers to create inspirational experiences. Though 3ds Max is a ranking tool for creating 3D models, we can also use alternatives to construct the objects like Maya, Cinema 4D, Blender, Light Wave 3D, depending on the designer's familiarity to the tools.

Before we model any real device in a 3D environment, parameters of each part of the real device need to be measured carefully. Then, in 3ds Max the model can be constructed using polygons, primitive geometry (standard primitives and extends primitives) and other geometric elements. In fact, most parts of the virtual equipment for control experiments can be described by basic symmetric objects, we can simply pile the spheres and cubes together to grab a draft of the whole plant. However, we may still find some elements cannot be well depicted by basic geometries. It is necessary to modify the basic object by geometric operations, such as Boolean, ProBoolean, ProCutter in Compound Objects List, and other modifiers in the Modifier List. Splines are commonly used to draw the profile of

an irregular geometry, which can be further modified using other modifiers, such as Extrude, to construct a complex 3D object.

In a 3D environment, the accurate coordinates of every joint and rotation pivot must be measured for both mathematical model and mechanical movement calculations. Similar to physical devices, the virtual devices are constructed in components so that each component can be programmed with a different movement. We can put all geometries with the same movement into one group. Consequently, we will have a fixed component group with elements which are not moving during the experiment and several component groups with elements of different movements. Thus, mechanics of the model can be described by several movements of these component groups. Each component will be exported in 3DS format after rendering and later be programmed with movements in the Flash Builder environment.

3.1.2 Mechanical Characteristic Design

Mechanics determines the physical movements of devices, which is created in Away 3D using real device data. Away3D is a non-commercial, open source, real-time 3D engine that relies on the free contributions of many designers and developers from within the Flash community. First, 3D models need to be imported into Away3D. Many formats can be adopted for saving models in 3ds Max. In this application, 3DS format model will be imported into Flash Builder for animation programming. Away3D has the advantage of Stage3D API and enables 3D GPU acceleration,

which indeed offers impressive visual effects. Scenes can be rendered up to a million triangles per frame, maintaining a steady 60 fps performance. Models can be easily imported, rendered and animated into web applications. Then, we can program with Away3D functions, compile the ActionScript codes and run the application. At last, a shock wave flash (SWF) file is generated and integrated into 3D-NCSLab for the real-time experiment.

Different devices have different mechanical structures. Some movements are linear and can be depicted by mathematical equations. However, other movements are hard to describe by one equation. A complex movement can either be described using approximation method or be decomposed into a combination of simple movements. Simple movements in 3D coordinates can be classified into two categories, the rotation and the translational motion. The mechanical characteristics can be designed in three steps as follows.

The first thing we should know is which data can be measured by real sensors. To design the same mechanism as the real device, we can only use data received from sensors instead of using state variables from a mathematical model. For example, we are not going to describe a movement using velocity variables if there are actually no velocity sensors in the real device. Sensor data can be described in the 3D environment by angle θ for rotation and x, y, z for movement along X, Y, Z axis. All the component movements can be described as $P(x, y, z), F(\theta)$, which can be calculated using sensor data and mechanical parameters of the device.

The next step is to decompose complex movement into a combination of several simple movements. M can be used as translational motions and R as rotations in the 3D environment. For translational motions, $P(x, y, z)$ is used to set the amount of movement long X, Y, Z axis. For rotations, the pivot point V and direction vector N need to be designated besides the rotation angle $F(\theta)$. So, the whole mechanical movement C can be described with (1), where m is the number of complex movements the device contains, n is the number of rotations decomposed from one complex movement.

$$C = \sum_{i=1}^m \left(M_i(P_i(x, y, z)) + \sum_{j=1}^n R_{ij}(F_{ij}(\theta), V_{ij}, N_{ij}) \right) \quad (1)$$

The final step is to transform materials prepared above into animation by writing ActionScript codes with Away3D API in Flash Builder environment. Generally, it is easy to realize the basic translational motion and rotation. Sometimes it is not a trivial task to rotate a component around an arbitrary point in space. However, it can be made a little simpler by taking advantage of containers. A component can be bound to a container, then it will automatically follow the movement of the container, thus this movement can be omitted and only other movement are needed. Usually a component and its container are connected physically, and the container has less degree of freedom. In addition, the component's movement can be calculated by the mechanical structure and the movement of the container.

3.2 Design of Ball and Beam Device

The virtual ball and beam device is chosen to illustrate the efficacy of the proposed method. The ball and beam device is a popular textbook example in the control theory and a controller is required to control the position of the ball on the beam. In this case, the ball and beam device is disassembled into five parts: base (components which are unable to move), ball, beam, lever arm, and gear. The size of each component is measured carefully to construct the model in the 3D environment.

Fig. 7 shows the structure of ball and beam system. When the servo gear turns by angle θ , the lever arm makes the beam rotate from the horizontal position. Then, the ball will roll on the inclined beam by gravity. An incremental encoder is adopted to measure the position of the servo. There is also a linear sensor in the groove of the beam to measure the position of the ball. From the data captured by sensors, the real position of the ball x and rotation angle θ of gear can be obtained. In a real time experiment, ball position x can be obtained from system simulation on control model, such as a transfer function model. But, to simulate the whole system kinematics in a 3D animation, how the beam and the lever arm move according to θ needs to be figured out, which cannot be obtained from the control model. Given an original position where the beam stands horizontally still, the joints are marked as A, B and C according to Fig. 7. When the gear rotates by angle θ , the joints are marked as A, B' and C' . D is used to mark the intersection of the horizontal line through A and the vertical line through C' . First, in right triangle ADC' , β can be calculated by (2).

$$\beta = a \tan \frac{S+r \cdot \cos \theta}{H-h-r \cdot \sin \theta} \quad (2)$$

Then, d is calculated via (3).

$$d = \frac{S+r \cdot \cos \theta}{\sin \beta} \quad (3)$$

Angle α can be derived in triangle $AB'C'$ using (4), then the horizontal rotation angle of the beam is computed as $\alpha + \beta - \pi / 2$.

$$\alpha = a \cos \frac{L1^2 + d^2 - L2^2}{2 \cdot L1 \cdot d} \quad (4)$$

Also γ is needed in the same way as α to show the vertical rotation of the lever arm by $\gamma - \beta$. The motion of the lever arm is complicated, but it can be decomposed into two parts, a circular motion which is concentric with the gear circle, and another circular motion base on the former motion.

$$\gamma = a \cos \frac{L2^2 + d^2 - L1^2}{2 \cdot L2 \cdot d} \quad (5)$$

The mechanical movements of ball and beam device can be described according to (1), by the following expressions:

$$\begin{aligned} \text{Gear:} & R(\theta, O, Z) \\ \text{Lever arm:} & R(\theta, O, Z) + R(-\theta - (\gamma - \beta), C, Z) \\ \text{Beam:} & R(\alpha + \beta - \pi / 2, A, Z) \\ \text{Ball:} & M(x, 0, 0) + R(\alpha + \beta - \pi / 2, A, Z) \end{aligned}$$

where Z equals vector $(0, 0, 1)$ and defines the direction of rotation, and O is the center of gear.

The gear can be chosen as the container of the lever arm.

So, when the gear rotates, the lever arm moves with the gear too. Similarly, the ball can be bound to the beam and expressions will be simplified as:

$$\begin{aligned} \text{Lever arm: } & R(-\theta - (\gamma - \beta), C, Z) \\ \text{Ball: } & M(x, 0, 0) \end{aligned}$$

The expressions are basic movements with detailed parameters that can be easily realized using Away3D functions.

4 ASSESSMENT

In order to evaluate the effectiveness of 3D-NCSLab on students' learning, two groups of students are compared by their subsequent performances in the control theory course from 2015 to 2016. In addition, two types of surveys were collected from students. At last, a cost comparison is given from various aspects to show advantages of described approach.

4.1 Similar Learning Process

In this section, we focus on how students master equivalent material and develop equivalent skills with a purely physical lab set up against a similar learning experience for the student using the virtual lab.

The successful application of purely physical experiment requires more theoretical background so that students' safety is guaranteed and the damage by mal-operations can be avoided. Physical experiments are usually open to students at the end of their theoretical courses. Therefore, students cannot make use of the experiments to enhance their comprehension of the theoretical concepts being taught. Instead, 3D-NCSLab brings no safety issues, and enhances the system robustness by assigning users proper access rights to avoid mal-operations like deleting

important files. Working on the virtual equipment at the very beginning of their theoretical courses can give students the big picture up front, so that they know they are going to solve some practical problems using knowledge being taught in other courses. They can get better understanding of what they learn by taking these theoretical concepts into practice. The specific learning processes are given in Table 2. During the virtual experimental processes,

TABLE 3

VIRTUAL DEVICES FOR CONTROL EXPERIMENT

Lab Name	Device Name
Inverted Pendulum	Linear 1-Stage Inverted Pendulum
	Linear 2-Stage Inverted Pendulum
	Rotary 1-Stage Inverted Pendulum
	Rotary 2-Stage Inverted Pendulum
	Pendulum
	Swing Up Control
Process Control	Single Tank
	Double Tank
	Triple Tank
	Cascade Double Tank
	S100 Pressure System
	S100 Liquid Lever System
	APC1001 Temperature System
	APC1001 Flow System
Servo Control	Torque Motor
	DC Motor
	Asynchronous Motor
	Stepping Motor
Motion Control	Ball and Beam
	Magnetic Levitation
	Ball and Plate
	Three DOF Hover
	Two DOF Hover
Innovation Lab	Gyroscope
	Industrial Plant Emulator
	Rectilinear Plant
	Torsional Apparatus
	Vehicle Formation Control
	Missile Trajectory Design
	Satellites Formation Control

TABLE 2

VIRTUAL DEVICES FOR CONTROL EXPERIMENT

	Virtual lab	Physical lab
1	Learn how to use the system through session 1. The teacher gives examples on how to use the platform.	Pay attention to the warnings. The teacher introduces the system and gives a demonstration of real-time experiment.
2	Read manuals of virtual device.	Read manuals of physical device.
3	Run demos: Download the algorithm into control unit, and run the 3D real-time experiment.	Run demos: run the control file in external mode in Simulink to control the inverted pendulum.
4	Design a controller according to the mathematical model, then run simulation until a satisfactory result is obtained.	Design a controller according to the mathematical model, then run simulation until a satisfactory result is obtained.
5	Connect 3D model to the control unit by selecting signals from the algorithm.	Connect inverted pendulum to the control card on the computer.
6	Control 3D virtual device. Tune parameters to get a better performance.	Control real device. Tune parameters to get a better performance.

each student must experiment on four different devices. Instead, only one experiment is compulsive in a purely physical experiment for the limited resources and the large number of students. Students are separated into groups, and each group has at least 5 members. Virtual experiments can be made either during laboratory sessions or in their personal time. Other merits of using 3D-NCLab are sharing and cooperation. Students can share their algorithms and carry out cooperative experiments by virtue of the communication modules of control units.

4.2 Results and Evaluation

The system has been applied to the creative automatic control experiment course offered by school of astronautics in the Harbin Institute of Technology (HIT), China. The experiment is used as a complement for the undergraduate course of automatic control theory (teaching about control systems and technology), to enhance student comprehension of the material taught. There are thirty virtual devices

TABLE 4
EXPERIMENTAL CONTENTS AND ASSIGNMENTS FOR TEN SESSIONS

Session 1:	Introduction to the learning system. Introduce the system and basic theoretical concepts to students. Introduce the development process of the virtual lab and relevant development tools. Students need to get familiar with the platform, run the demos prepared for each experiment to have better understanding of the learning system. At last, each group will choose a virtual device as their main experimental subject.
Session 2:	Change parameters of the given algorithm and observe the result. Read the manual of ball and beam system. Change parameters of controller and observe the result, then analyse structure of the system and its control principle. Explain feedback control, LQR algorithm and necessary control principles to students.
Session 3:	Add interference to the model, and then modify the given algorithm to control it. Add square wave, triangular wave and sine wave to the system as interference, then observe the result. Adjust parameters of the controller to meet expectations. Analysis performance of the system, such as rise time, settling time and overshoot.
Session 4:	Experiment on a modified model by students themselves. Design a controller for the system, then tune parameters to make it work. Analyse how each parameter affects the whole system's performance.
Session 5:	Work on the system using another control method. Explain the pole-placement method, including how to solve characteristic equation, figure out the value of poles and zeros, and how to get feedback gain K using Matlab tools. Design a controller using pole-placement method: build simulation block first, then adjust parameters, run the simulation until students can get satisfactory result. Compile the algorithm and download it into the control unit, then run the 3D real-time experiment.
Session 6:	Design a controller for equipment with interference. Add white noise to the system as interference, then observe the result. Design a controller and a filter for the system, then adjust parameters of the controller to meet expectations. Analysis performance of the system according to different parameters of the filter
Session 7:	Cooperative control using cascade PID algorithm. Adjust the parameters of the inner loop first, then adjust the outer loop using send and receive modules for communication.
Session 8:	Experiment on a second device.
Session 9:	Experiment on a third device and carry on experiment on a fourth device after school as an assignment.
Session10:	Summary and final assignments. All groups will submit their report in two weeks including experiment results as well as their feelings and experiences in learning process.

deployed in five laboratories for experiments, and the detailed information can be seen in Table 3. The enrollment of the course was 35 and 38 respectively during the fall semesters in 2015 and 2016. The experimental group consists of participants who used virtual lab, and the control group consists students who did not choose the virtual experiment course. A comparison of their average marks in subsequent course exam is shown in Table 5, in the two-year consecutive analysis, higher average marks of experimental group shows positive evidence on the effectiveness of using the virtual lab.

A Project-Based Learning strategy has been developed

TABLE 5
RESULTS OF CONTROL THEORY COURSE

Statistics	Semesters 2015	Average Marks	Semesters 2016	Average Marks
Participants	241	71.8	252	74.2
Experimental Group	35(14.5%)	74.3	38	78.8
Control Group	206(85.5%)	71.4	214	73.4

in [34], which has balanced theoretical and practical contents. Compared with it, we mainly focus on practical contents. To teach students how to apply knowledge from textbook into practice using 3D virtual lab, we organized ten experimental sessions distributed in the same period when control theory course was open. A lecture was given in the first session to provide students a general overview about the whole platform and resources available for experiments. More specifically, the contents of all ten sessions are listed in Table 4. Except some necessary contents given by a teacher, students could carry out experiments in most sessions. They can work well on their assignments following the instructions of the manuals and documents provided by the platform. In some circumstances when a student facing a thorny problem, the teacher would give him or her some tips first. If it does not work, then further help will be given to the student in details. In addition to general sessions, students are encouraged to use the virtual labs at any time to speed up their learning processes. The server has been running well in 24 hours every day during the past two years, which shows the stability of the system.

4.3 Student Survey

The first survey was a questionnaire including twenty

statements to assess how satisfied the student is with each statement. The second one was an in-class workshop for students to freely comment on the system. Some statements in the questionnaire are shown as:

- 1) You can apply knowledge studied into practice.
- 2) The 3D models are realistic and visually appealing, and the system can increase your interest of learning automatic control theory.
- 3) It is convenient and high-efficient that you can also carry out experiments outside the laboratory at any time.
- 4) The interfaces of the system are friendly and easy to use.
- 5) The instructions and documents offered in the system are adequate for you to carry out experiments by yourself.
- 6) The virtual experiment in 3D-NCSLab is very close to real experiment.

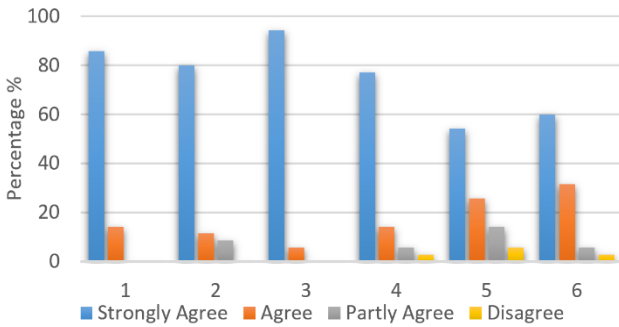


Fig. 8. Survey results to statement 1-6.

The survey results on the whole show a positive feedback in Fig. 8. Students are satisfied with most part of the system with “strongly agree” or “agree”. From question 5 we knew that some students did not satisfy with the documents offered by the system. In the later workshop discussion, we learned that although they were in the automatic control course, they had not finished the course at that time. So, we improved the documents according to students’ feedback and the instructions were modified to cover preliminary knowledge. Question 6 focused on the comparison between real experiments and virtual ones, and most students agreed that 3D virtual experiments were close to real ones. But, there is still a long way to go before real devices can be replaced by virtual ones, because very detailed simulations to the real device are quite challenging. However, virtual devices for education do not need too many details for research purpose. 3D virtual devices have great

advantages in saving expenses over real ones. Virtual experiments are high-efficient and absolutely safe, students can get access to the systems from any place at any time. The survey shows that 3D-NCSLab is an efficient and appealing platform for control education.

4.4 Cost Evaluation

Virtual devices not only can provide students similar learning experiences as physical ones, but also have advantages for universities to save expenditure on experimental facilities. A comparison is made between a virtual lab and a physical lab, both labs are established by school of astronautics in HIT, China. One set of virtual lab system (Fig. 5) can simultaneously provide experiments for eighty students. In contrast, the physical lab contains four devices: single tank, double tank, inverted pendulum and ball and beam system. A computer is also required for each device. Instead, students can use their own computers in a virtual lab.

Moreover, usually two faculty members are needed in the experimental process to keep an eye on students for their safety; and an extra staff is required for the maintenance of both equipment and laboratory. Virtual labs also can save space resources for universities, the specific comparison is listed in Table 6. The figures, \$30,000 vs. \$48,000, only include costs to the university, and all students have laptops for other purposes before taking the class.

5 CONCLUSIONS AND FUTURE WORK

In this paper, the approach to design 3D equipment for large scale application is presented. Architecture of 3D-NCSLab and 3D technologies on modelling, rendering, texture and lighting are discussed. The mechanical structure is analysed to design the accurate 3D dynamics compared with real devices. Advanced mathematical methods to simulate the details of real devices will be studied in our future work.

HIL simulations with extensible web-based control units can offer a flexible and creative way to provide experiment for large-scale users. 3D virtual equipment can be a valid solution to the large demand of advanced educational facilities.

The virtual devices can save expenses for universities and promote creative experiments. Advanced virtual instruments should have similar features with real ones; they not only meet our daily experiment demand, but also provide flexibilities in the way we experiment. Students can benefit from the abundant virtual resources and get strong motivation toward the appealing application. Furthermore,

TABLE 6
COST COMPARISON

	Equipment cost (US dollars)	Maintenance	Faculty	Staff	Space
Virtual lab	30,000 (students use their own laptops)	Mainly software update	1	0	Put the server in the IT room, sessions can be held in ordinary classrooms.
Physical lab	48,000 (4 sets of equipment, 4 computers included)	Need special care for hardware	2	1	Need a special large room to hold 4 sets of equipment including 4 computers and 30 students.

students can save a lot of time by arranging spare time for experiments. Survey result shows that the system is qualified to provide high-quality virtual control experiments for large-scale education.

The 3D applications proposed in this paper are based on Flash, which seems to be an outdated technology. Moreover, there are trends of using mobile devices such as smartphones or tablets to carry out experiments. We did a lot of research on other possibilities to create the GUI. In consideration of 3D performance and the requirement to user's programming skills, Unity3D is adopted because its applications can be deployed into many platforms, such as Windows, Mac, WebGL and Android. Our platform support Unity 3D well in the 3D web application development. The communications between web applications and experiment engines have been tested by writing scripts in either Javascript or C#. In our future work, a new edition of virtual lab will be developed to support a wide range of platforms.

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